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Modifications of Nucleons in Nuclei

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I summarize recent results and discuss upcoming and planned experiments that attempt to elucidate how the structure of nucleons might be modified by nuclear binding.

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1 Introduction

Nuclear Physics, from its beginnings in the 1930's up to the present day, has had tremendous successes describing the masses, energy levels, shapes and other properties of nuclei as well as their structures and reactions in terms of microscopic (or collective) models where nuclei are composed of individual nucleons interacting with each other through the exchange of mesons, perhaps augmented by a hard repulsive core. In particular, state-of-the-art calculations including sophisticated nucleon-nucleon potentials [1, 2, 3, 4, 5], or based on fully relativistic nuclear models [6], can describe many features of the nuclear response in elastic, quasi-elastic and inelastic electro-weak scattering off nuclei. While some care has to be taken to incorporate the required conservation of energy and momentum (as well as current conservation) in the description of such processes (because of nuclear binding), these models are remarkably successful in spite of ignoring any internal structure of the nucleons making up nuclei, or at least any modification of that structure from that of free nucleons.

In stark contrast, we know that the ultimate theory describing nucleons and nuclei is Quantum Chromo Dynamics (QCD). In this framework, both free nucleons and nuclei are bound (stationary) systems containing quarks, antiquarks and gluons interacting through their color couplings. From this perspective, the main distinction between a nucleon and a nucleus is just the net difference between the number of quarks and antiquarks, which is equal to $3A$ (A being the baryon number of a nucleon or nucleus). At first blush, it is then quite surprising that nuclei should appear as a collection of nucleons at all, let alone (largely) unmodified ones. However, due to the unique properties of QCD, namely confinement at large distance scales and spontaneous chiral symmetry breaking, such a “clustering” into nucleon-like sub-structures together with meson exchange currents can be understood at least qualitatively. Yet, it would be very surprising, within this framework, if there were *no* differences between the internal structure of those “nucleon-like constituents” of nuclei and free nucleons.

A comparison with the (much more precisely calculable) theory of Quantum Electrodynamics (QED) may illuminate this point. In this theory, the structure and the mass of the electron are ultimately due in part to its virtual fluctuations into electrons plus photons, additional electrons and positrons, which are suppressed by powers of the electromagnetic coupling strength, $\alpha_{EM} \approx 1/137$. As a consequence, one should expect, at least in principle, a modification of the structure of an electron bound in, say, a hydrogen atom vs. that of a free one. Indeed, one can interpret observations such as the Lamb shift in hydrogen as a consequence of this internal structure modification. However, because the binding energy of the electron in hydrogen is only a small fraction of its mass ($\alpha_{EM}^2/2 = 0.0027\%$), the effect is tiny (about a million times smaller than the applicable binding energy) and can only be observed with the extreme precision available to modern atomic spectroscopy. At the other end of

the scale, there is no question that atoms themselves are significantly modified when bound into molecules - the eigenstates of the electrons in a hydrogen molecule have completely different shapes than those in hydrogen atoms. This corresponds to a much larger relative binding energy in this case - H_2 is bound by about 1/3 of the binding energy of free hydrogen atoms.

It seems clear then that for the case considered here, nucleons bound in nuclei, one should expect binding effects intermediate between the two extreme examples above, since the binding energy of individual nucleons in nuclei lies somewhere between 0.12% and 0.9% of their masses. Indeed, there are several experimental results that appear to unambiguously confirm some modification of nucleon structure in bound nucleons; some of these results are discussed in the next section. Nevertheless, a quantitative comparison between such experimental signals and rigorous QCD-based predictions remains elusive, due both to the difficulties of reliable QCD calculations in the low-energy regime and due to the considerably larger uncertainties in hadronic experiments and their interpretation (including the above-mentioned “trivial” binding effects due to energy-momentum and current conservation), compared to, e.g., atomic spectroscopy. This is the reason for the oft-cited adage “Nuclear modifications of nucleon structure are like the Mafia in Sicily: everyone knows they are there, but it is very difficult to find hard evidence”.

2 Experimental Evidence

One of the earliest experiments showing incontrovertible evidence for the modification of nucleon structure inside the nucleus is the famous EMC experiment [7] which has been corroborated by a large number of experiments at many labs [8, 9, 10, 11]. These experiments show a significant reduction of the per-nucleon structure function $F_2(x)$ in the valence region, $0.2 \leq x \leq 0.8$ relative to that of a free nucleon, with a roughly linear behavior that is universal in shape for all nuclei, but with a slope that tends to increase for heavier and denser nuclei. A recent precision experiment at Jefferson Lab [12] has extended our knowledge of this EMC effect towards a range of lighter nuclei, including ^3He , ^9Be and ^{12}C . Surprisingly, it was found that the “EMC slope” does not follow a simple correlation with the average nuclear density of the studied nuclear species. Instead, as shown in Fig. 1, ^9Be shows a strong EMC effect somewhere between ^4He and ^{12}C , in spite of being a rather dilute nucleus (see inset in Fig. 1).

A closer inspection shows, however, that 8 out of the 9 nucleons in ^9Be are located inside tightly bound “alpha clusters”, with only the remaining neutron further out. Hence, the *local* nuclear density seen by most nucleons in ^9Be is much higher than the average, global density. This can be seen as strong evidence that the strength of the EMC effect (the magnitude of the slope) is determined by the local nuclear

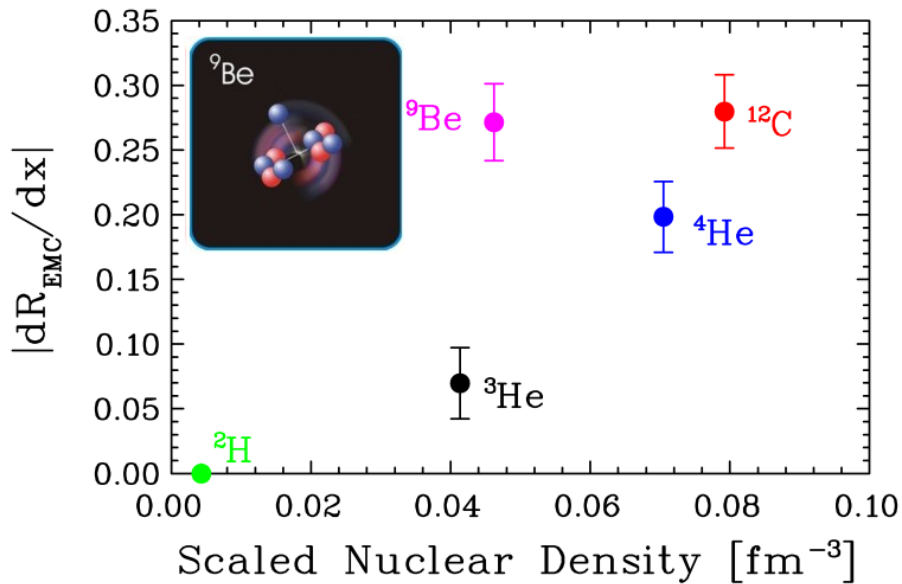


Figure 1: Slope of the ratio between bound and free nucleon structure functions with the scaling variable x , versus the average density of the nuclei investigated in [12]. Note that here, as usual, the EMC ratio R_{EMC} of structure functions is actually defined relative to the deuteron, which is only an approximation to the average of a free proton and a free neutron.

environment of the struck nucleon.

This conclusion is further corroborated by a comparison with another effect that should directly depend on the local nuclear density, namely the strength of short-range (high-momentum) nucleon-nucleon correlations inside nuclei. Indeed, it was found [13, 14] that this strength correlates nearly perfectly with the strength of the EMC effect over a wide range of nuclei, as shown in Fig. 2. This remarkable agreement seems to indicate that either nucleons in short-range (high-momentum) correlations contribute the bulk of the overall EMC effect (see, e.g., the model by Frankfurt and Strikman [15]), or that both the correlation probability and the EMC effect are governed by a common underlying feature, e.g., the local nuclear density (consistent with “quark-meson coupling” models like the one in [16]).

Most recently, a first attempt to measure directly the EMC effect in deuterium has been published [17], based on the data of the BONuS experiment [18] which, for the first time, attempted to directly extract the structure function F_{2n} of the free neutron. Within the (rather large) experimental uncertainties, strongly suggestive evidence of a EMC slope of order -0.1 was found (see Fig. 3), which is consistent with the extension of the straight line fit in Fig. 2 to $a_2 = 0$, corresponding to free nucleons.

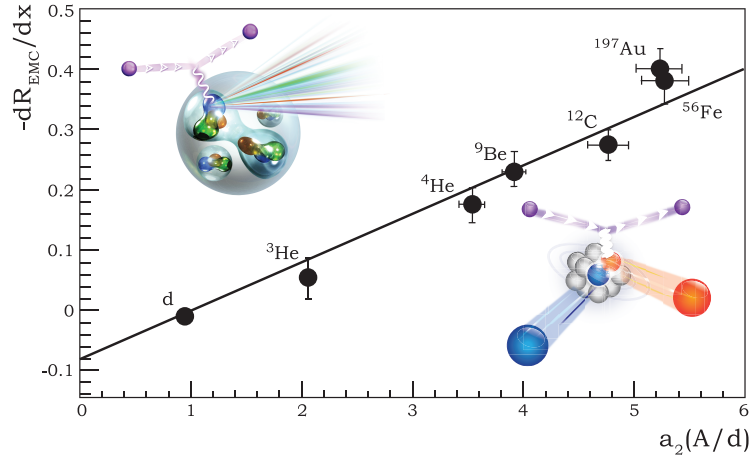


Figure 2: Correlation between the strength (slope) of the EMC effect (y -axis) and the relative probability to find a nucleon inside a high-momentum nucleon correlation (a_2) relative to the same probability in deuterium. a_2 measures the relative yield of DIS on a nucleus at large $x > 1.4$, where only high momentum nucleons can contribute to the strength of the response. A rich body of experimental evidence shows that these high momentum nucleons are nearly always paired with a partner of the opposite type and of nearly equal and opposite momentum; see elsewhere in these proceedings.

Beyond measurements of DIS on nuclei, experimental hints for nucleon modification in nuclei also come from form factor measurements on bound nuclei. For instance,

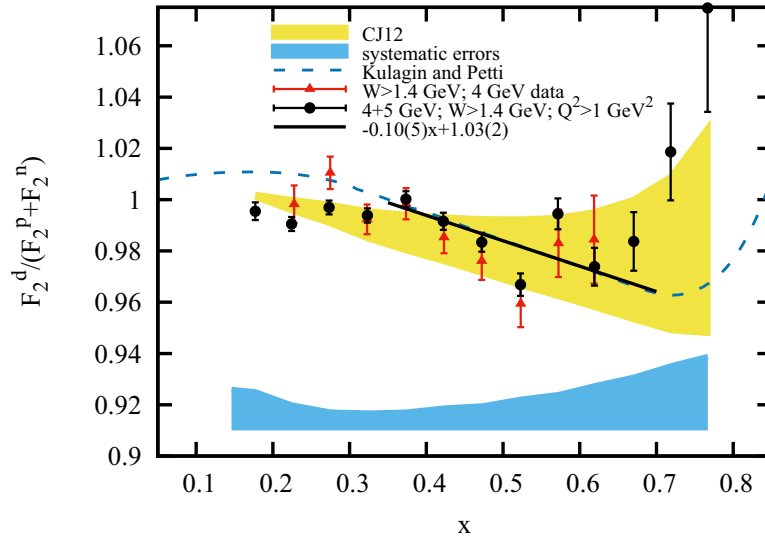


Figure 3: EMC effect in Deuterium [17]. See text for explanation.

a recent measurement [19] of the ratio of electric to magnetic form factors of a proton bound in ^4He , relative to a free proton, found a substantial reduction of this quantity that is not easily explained without invoking modifications of the nucleon size inside a nucleus.

3 Ongoing and Planned Experiments

Given the fundamental importance of understanding the QCD structure of bound nucleons, a large array of new experiments are either underway or planned to further study in detail various aspects of the EMC effect and hopefully clarify the underlying mechanism. These experiments use a variety of probes to elucidate the dependence of the EMC effect on quark flavor and nucleon type (proton vs. neutron), on the virtual photon polarization (longitudinal vs. transverse) and on nucleon spin. Further experiments aim to tackle directly the question whether high-momentum nucleons in the nucleus are more strongly modified than average, “mean field” nucleons. High precision measurements of the free neutron structure will allow us to directly extract the EMC effect in deuterium, the lightest and least dense nucleus. Finally, further measurements of in-medium nucleon form factors are ongoing, for instance at the MAMI electron scattering facility. Below we give a brief summary of some of these experiments; many of them are described in detail elsewhere in these proceedings.

Among the alternative probes used to study the EMC effect, DIS with neutrinos and Drell-Yan experiments play a prominent role. Experiments like *Minerva* that study the interaction of neutrino beams with nuclear targets open a different window on nucleon modifications in medium, since they are sensitive to different combinations of quark flavors. In fact, the famous “NuTeV anomaly” [20], while originally interpreted as a violation of Standard Model expectations, might indeed be (at least partially) explained [21] by non-trivial isospin-dependent nucleon structure modifications in the iron target used by NuTeV. Similarly, Drell-Yan experiments like *SeaQuest* are particularly well suited to access the largely unexplored contribution of sea quarks and antiquarks to the EMC effect.

The bulk of new experiments to further study the EMC effect are planned for the energy-upgraded Jefferson Lab (Thomas Jefferson National Accelerator Facility, Newport News, VA). The upgrade, which is nearly complete, together with extensive new experimental facilities in four halls, provides for significantly higher energy (11-12 GeV), high intensity electron and photon beams well-suited for high-precision experiments in the valence region. These facilities will be used to continue the study of the “classical” EMC effect in DIS on nuclei, with unprecedented precision, kinematic reach and a plethora of nuclei. In particular, experiment E12-10-008 will study, for the first time, many isotopes of the same elements over a large range in nucleon number A , e.g. $^3\text{--}^4\text{He}$, $^6\text{--}^7\text{Li}$, $^{10\text{--}11}\text{B}$ and $^{40,48}\text{Ca}$. These data will allow us to unam-

biguously extract the difference between proton and neutron structure modifications in the nucleus, in particular once the new free neutron data from experiments like “BONuS12” and “Marathon” are available. The latter experiment will also directly measure the EMC effect for the isospin pair ${}^3\text{He}/{}^3\text{H}$. These results will be augmented with precision measurements of the ratio R for longitudinal vs. transverse virtual photon absorption on nuclei.

Another degree of freedom that has not been experimentally explored so far at all is the spin of the nucleon. While the EMC was also the first (of many) experiments to find a surprisingly small contribution of quark spins to the overall nucleon spin, so far we don’t have any information on the “squared EMC effect”, namely the modification of nucleon spin structure functions for nucleons bound in nuclei. Such measurements could play a decisive role distinguishing between various models of the EMC effect, since they make strikingly different predictions for the ratio of bound to free spin structure functions. Experiment E12-14-001 will measure the ratio of the spin structure function $g_1(x)$ and the asymmetry $A_1(x)$ for the nucleus ${}^7\text{Li}$ over the free proton. Figure 4 shows the expected results compared to various model expectations.

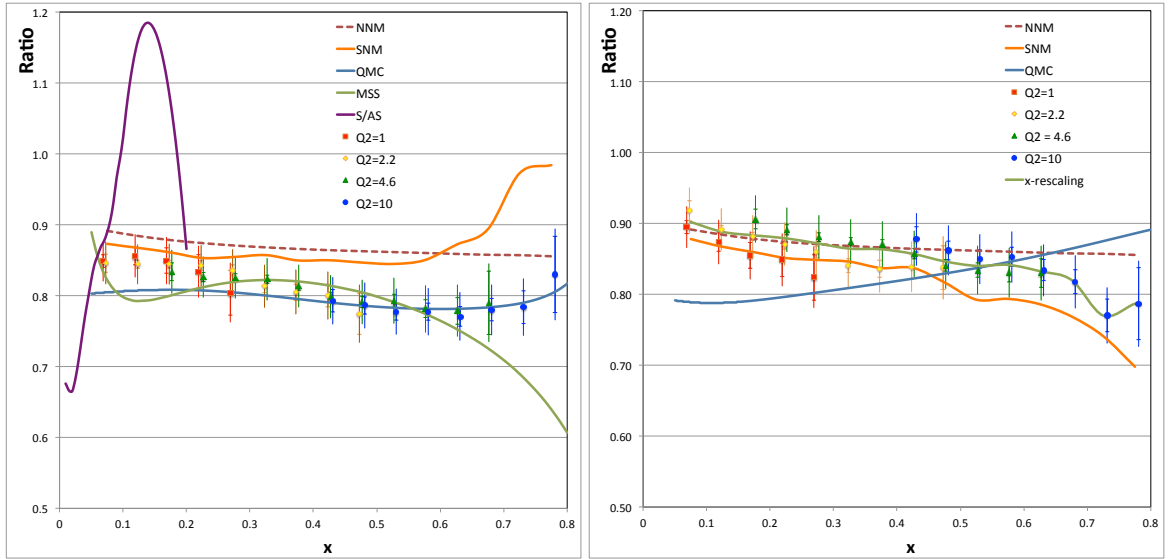


Figure 4: Expected results for experiment E12-14-001 at Jefferson Lab. The l.h.s. shows the ratio of spin structure functions g_1 for ${}^7\text{Li}$ over the free proton, while the r.h.s. shows the same ratio for the asymmetries A_1 . The inner error bars represented the expected statistical uncertainties, and the outer ones include the systematic uncertainties. The various model curves shown are from a simple additive “nucleons-only” model without EMC effect and with (SNM) and without (NNM) accounting for nuclear Fermi motion, as well as a “Quark-Meson Coupling” type model [22] (QMC) and two alternative models [23, 24].

Further studies involving polarized nuclei aim to measure the tensor-polarization structure function b_1 . There are also plans to study Deeply Virtual Compton Scattering from nuclei (in particular ^4He) to find evidence for modifications of Generalized Parton Distributions (GPDs), following a first proof-of-principle experiment with Jefferson Lab’s 6 GeV beam. Since GPDs encode both the longitudinal momentum and transverse spatial distribution of quarks, they can be used to test models where the EMC effect is due to nucleon “swelling” in the medium.

Finally, several experiments will use the technique of “spectator tagging” to directly study DIS on fast-moving nucleons inside the nucleus. This technique was pioneered with 6 GeV experiments like “BONuS” [18] and involves the simultaneous detection of a scattered electron and a backwards-going spectator nucleon. BONuS applied this method, selecting slow-moving protons from a deuterium target, to tag nearly on-shell neutrons and measure their free structure functions. On the other hand, by measuring high momentum spectators, one can ensure that the electron scattering took place on a nucleon that was part of a short-range correlation, thereby accessing any possible enhancement of the EMC effect in such nucleon pairs. This will be exploited by experiment E12-11-107 (with proton spectators) and a companion experiment looking for fast backward neutrons, both with deuterium targets. Beyond that, plans are underway to extend this technique to heavier nuclei.

4 Outlook and Conclusions

Given the mounting experimental evidence, there can be hardly any disagreement that non-trivial nuclear binding effects on nucleon structure exist. Upcoming experiments, in particular at the energy-upgraded Jefferson Lab, will further sharpen this evidence and map out their detailed properties. A complete description of these nuclear effects is a necessary part of our understanding of the microscopic (QCD) structure of nucleons *and* nuclei, and therefore the manifestation of QCD in all strongly bound systems. It is also an important input for the interpretation of experiments that rely on nuclear targets to study fundamental physics - from neutrino scattering (see the famous NuTeV anomaly that is now considered to be at least partially due to nuclear effects) to the measurement of structure functions of the neutron, which by necessity involves nuclear targets. We can look forward to a new era of precision measurements, with commensurate advances in theoretical understanding, in this area. In particular, recent progress in ab-initio calculations of QCD bound-state properties on the lattice make fully microscopic models of nucleons *and* nuclei appear feasible in the not-too-distant future.

Ultimately, an electron-ion-collider as proposed by the US nuclear physics community will be required to complete our picture of parton distributions in momentum and space, both in nucleons and in nuclei. In particular, such a machine will be

uniquely suited to study the modification of gluon and sea quark distributions in a wide range of nuclei, and further elucidate the phenomenon of shadowing.

While we haven't quite solved yet the 30-year old puzzle posed by the original EMC measurement, we can finally look forward to a definite answer provided by the new accelerators, experimental methods and theoretical advances already in place or on the horizon.

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